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EXTREME ENVIRONMENTS TECHNOLOGIES FOR PROBES TO VENUS AND JUPITER

Jupiter / Venus probe concept

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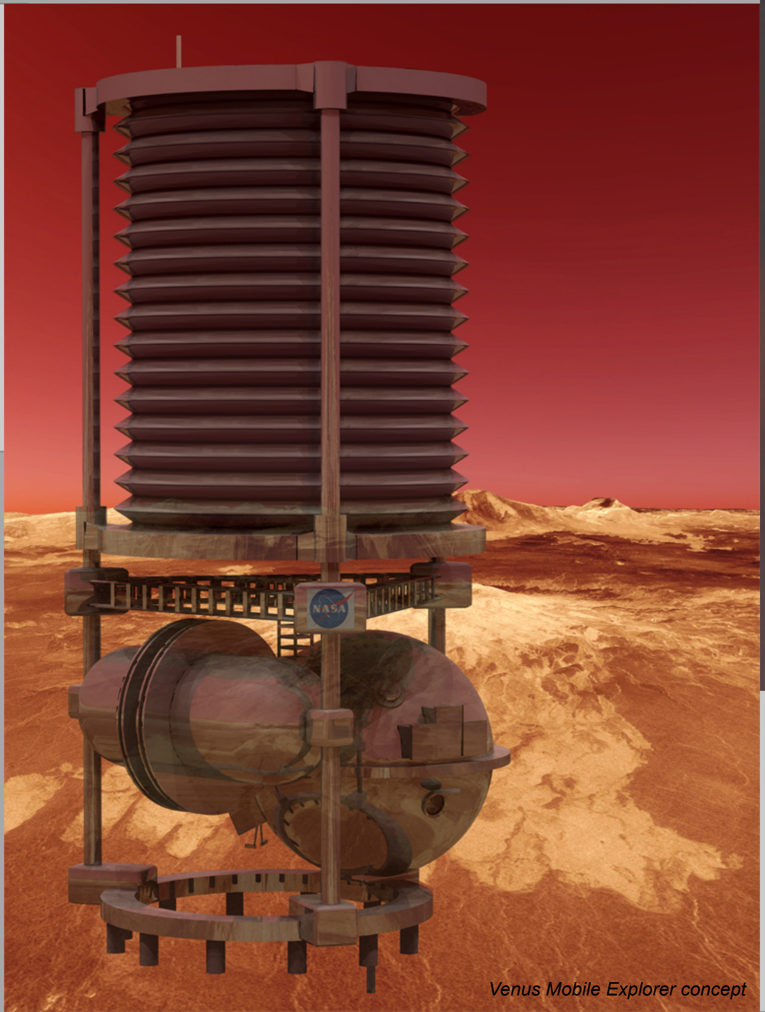

Venus Mobile Explorer concept

Presented by
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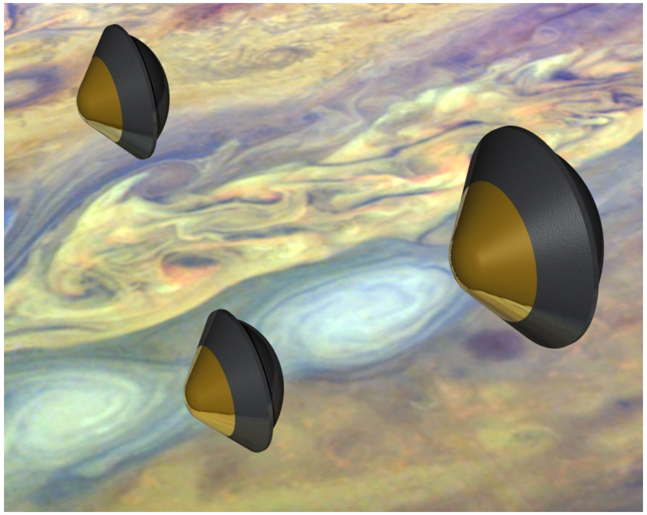
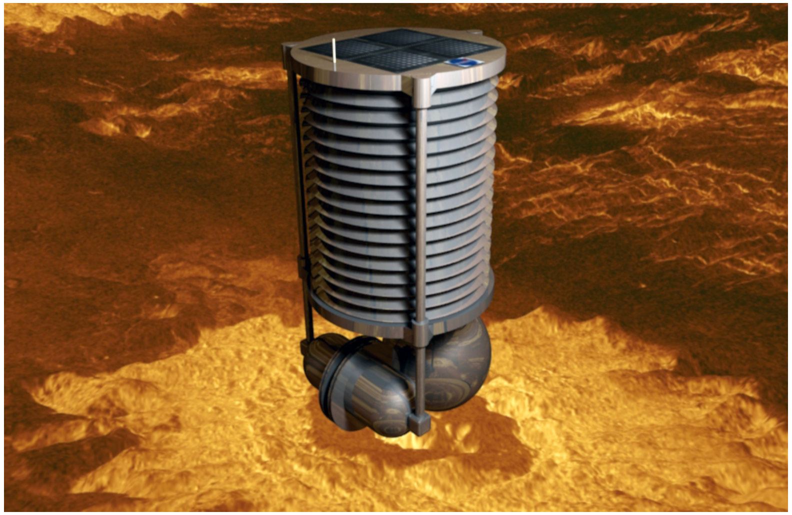
Any opinions, findings, and conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

Surface of Venus – as imaged by Venera 14a

- Introduction
- Extreme environments at Venus and Jupiter
- In-situ missions to Venus and Jupiter (past/present/future)
- Approaches to mitigate extreme environments for probes
  - Systems architectures
  - Technologies
- Conclusions



JDEP concept



VME concept

INTRODUCTION

- In-situ exploration of Venus and Jupiter represents **high priority science** objectives, as discussed in the:
  - **Decadal Survey** by the National Research Council (NRC)
  - NASA's 2006 Solar System Exploration **(SSE) Roadmap**

- For **Venus**:
  - In-situ exploration **at or near the surface** is recommended; where
  - The temperature and pressure conditions are **~480°C** and **~92 bars**
  - **Lifetime** of Venus Mobile Explorer measured in **weeks to months**

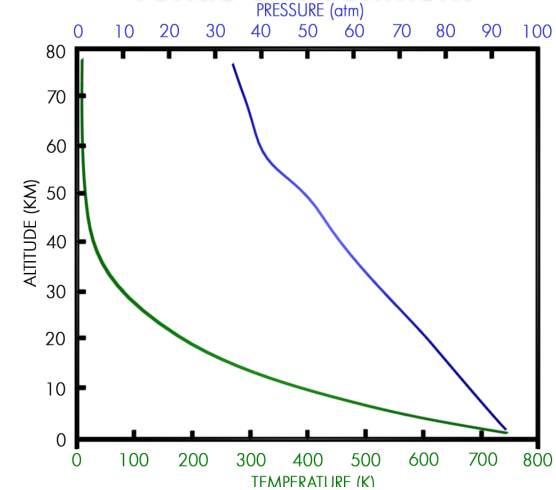
- For **Jupiter**:
  - **Deep entry probes** are recommended
  - Descending to ~250 km - measured from the 1 bar pressure depth
  - At this level the pressure is **~100 bars**; the temperature **>400°C**
  - **Lifetime** of Jupiter deep entry probes is measured in **1-1.5 hours**

- Technologies at Venus and Jupiter share commonalities
  - in mitigating these extreme conditions over proposed mission lifetimes,
  - specifically focusing on pressure and temperature environments.

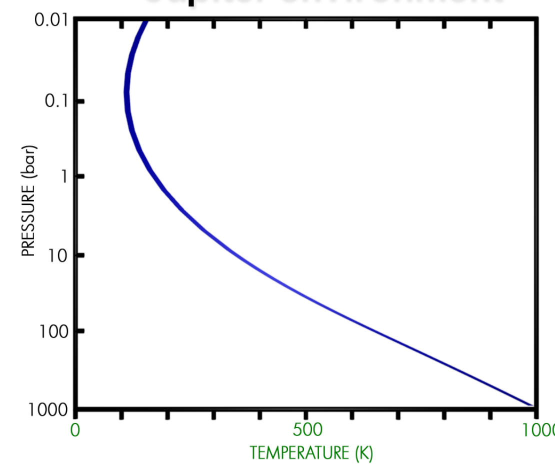
EXTREME ENVIRONMENTS AT VENUS AND JUPITER

	Venus	Jupiter
Atmospheric composition	CO_2 ~96.5%; N_2 ~3.5%; with small amounts of noble gases (e.g., He, Ne, Ar, Kr, Xe); small amounts of reactive trace gases (e.g., SO_2, H_2O,CO, OCS, H_2S, HCl, SO, HF).	H_2 ~85%; He ~14%; CH_4 ~0.2%; H_2O; NH_3; H_2S; organics, noble gases PH_3? CO?; Probably many others, especially at depth
Clouds	Aqueous sulfuric acid droplets between ~45 km and 70 km	NH_3: 0.25 - 1 bars; NH_4SH, (NH_3 + H_2S): 2-3 bars; H_2O: 5-100+ bars; Other clouds? Silicates?
Winds	Super rotating atmosphere; Zonal winds near the surface:~1 m/s; increasing up to 120 m/s at an altitude of ~65 km.	Galileo Probe saw an increase in flow speed with decreasing sunlight; Flow speed fairly steady below 5 bars; Maximum velocity just under 200 m/s
Temperatures	Greenhouse effect; Surface temperature ~460 to 480°C.	Min. ~110 K at the 0.1 bar; Increases with depth: ~165 K at 1 bar; >670K (>400°C) at 100 bars; >1000K at 1000 bars;
Pressure	Surface pressure ~92 bars. CO_2 is supercritical at this pressure	Deep entry probes target 100 bars

Venus environment

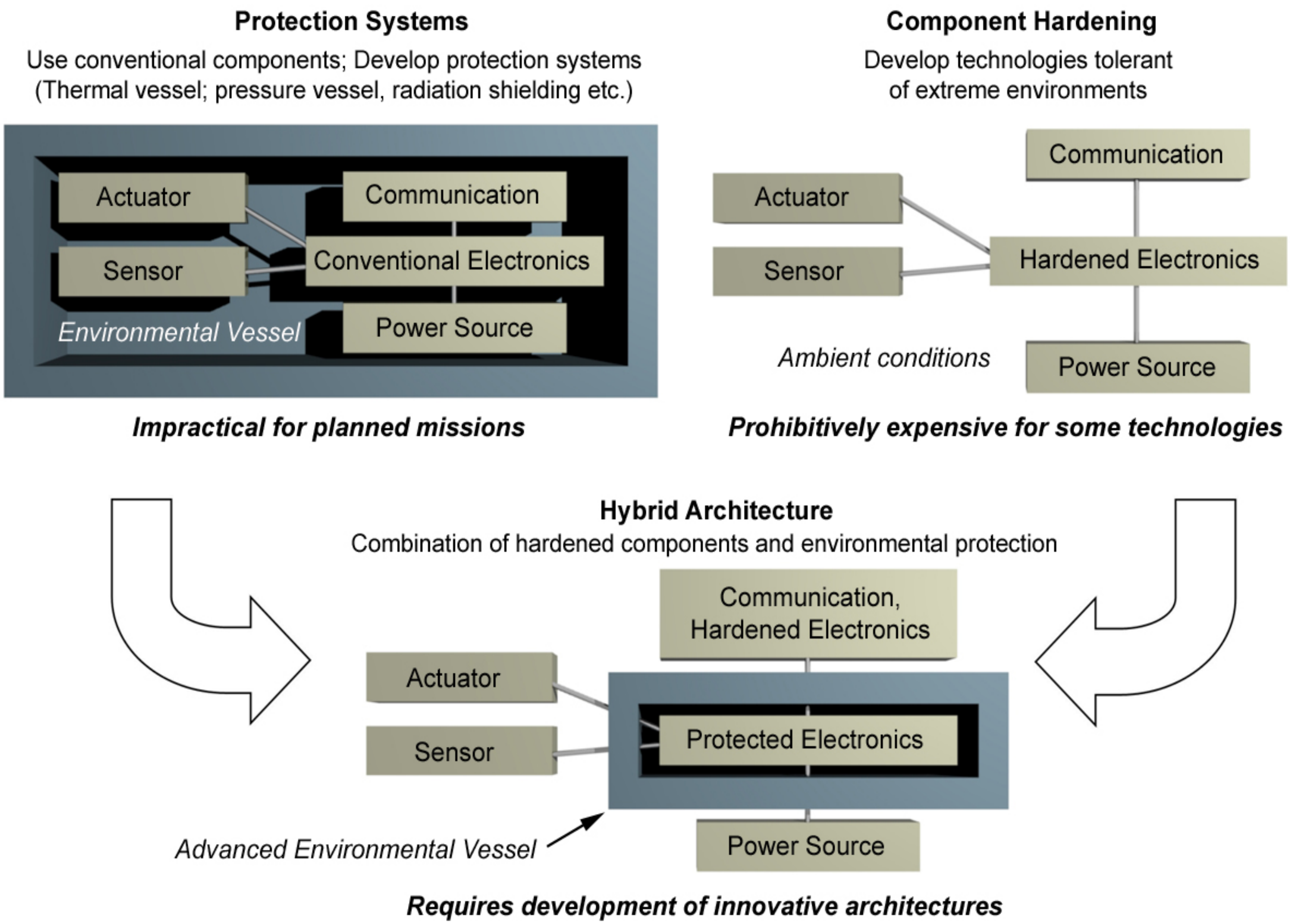


Jupiter environment



In-situ missions near the surface of Venus and deep in the atmosphere of Jupiter encounter **similar extreme environments**. **Similar technologies** could be used **to mitigate** these conditions.

Venus		
Probes	Pioneer-Venus Probes	Past (US)
	Russian Probe on EVE – Cosmic Vision	*Potential Future (ESA/FKA) (CV)*
Balloons	Vega Balloons	Past (USSR / Int.)
	VALOR (Venus Atmospheric Long-Duration Observatories for in-situ Research)	*Potential Future (US) (D)*
	European Venus Explorer (EVE) – Balloon element	*Potential Future (ESA/FKA) (CV)*
	JAXA Mid-Cloud Balloon	*Potential Future (JAXA)*
Landers	Venera Program	Past (USSR)
	Venus In-Situ Explorer (VISE)	*Potential Future (US) (NF)*
	Venus Mobile Explorer (VME)	*Potential Future (US) (F)*
	Venus Geophysical Network	*Potential Future (US) (F)*
	Venus Surface Sample Return (VSSR)	*Potential Future (US)*
Orbiter	Magellan	Past (US)
	Venus Express	Present (ESA)
	EVE – European Venus Explorer – Orbiter element	*Potential Future (ESA/FKA) (CV)*
	VESPER	*Potential Future (NASA) (D)*
Jupiter		
Probes	Galileo Probe to Jupiter	Past (US)
	Jupiter Deep Entry Probes (JDEP)	*Potential Future (US) (NF)*



Systems architectures for extreme environments can be categorized by:

- the **isolation** of sensitive materials from hazardous conditions;
- the development of sensitive materials, **tolerant** to hazardous conditions;
- and an appropriate **combination of isolation and tolerance**.

KEY EXTREME ENVIRONMENT TECHNOLOGIES

Technology needs could be categorized into three general areas:

1. **Environmental protection** technologies providing isolation from extreme environments;
2. **Environmental tolerance** for exposed components or systems;
3. **Operations in extreme environments**.

- Protection systems:
  - Hypervelocity Entry
  - Pressure Mitigation
  - Temperature Mitigation
- High-Temperature Electronics
- Power Storage
- Power Generation
- Mobility Technologies
  - Balloon and Parachute Materials
- Sample Acquisition & Mechanism
- Telecommunication Issues
- Testing for Extreme Environments

HYPERVELOCITY ENTRY

- The **Thermal Protection System** (TPS) protects (insulates) a body from the extreme heating encountered during hypersonic flight through a planetary atmosphere.
- **Ablative materials**, such as fully dense **Carbon-Phenolic** (C-P), can tolerate **~1 kW/cm^2**.
- **TPS mass fraction** ranges from **~12% for Venus missions** to as high as 50-70% for Jupiter probe missions.

Galileo heritage aeroshell concept

Technology development could reduce TPS mass fraction by ~25% to 50%.

PRESSURE & TEMPERATURE MITIGATION

- Extending mission lifetime beyond 1-2 hours will require **lighter pressure vessels** & **thermal control** systems that can keep all components operational.

- **Thermal control** methods rely on
  - **isolation** (aerogel, multi-layer insulation) from external heat sources,
  - **removal of self generated heat** by
    - local thermal energy storage (phase change materials), or
    - by active cooling.

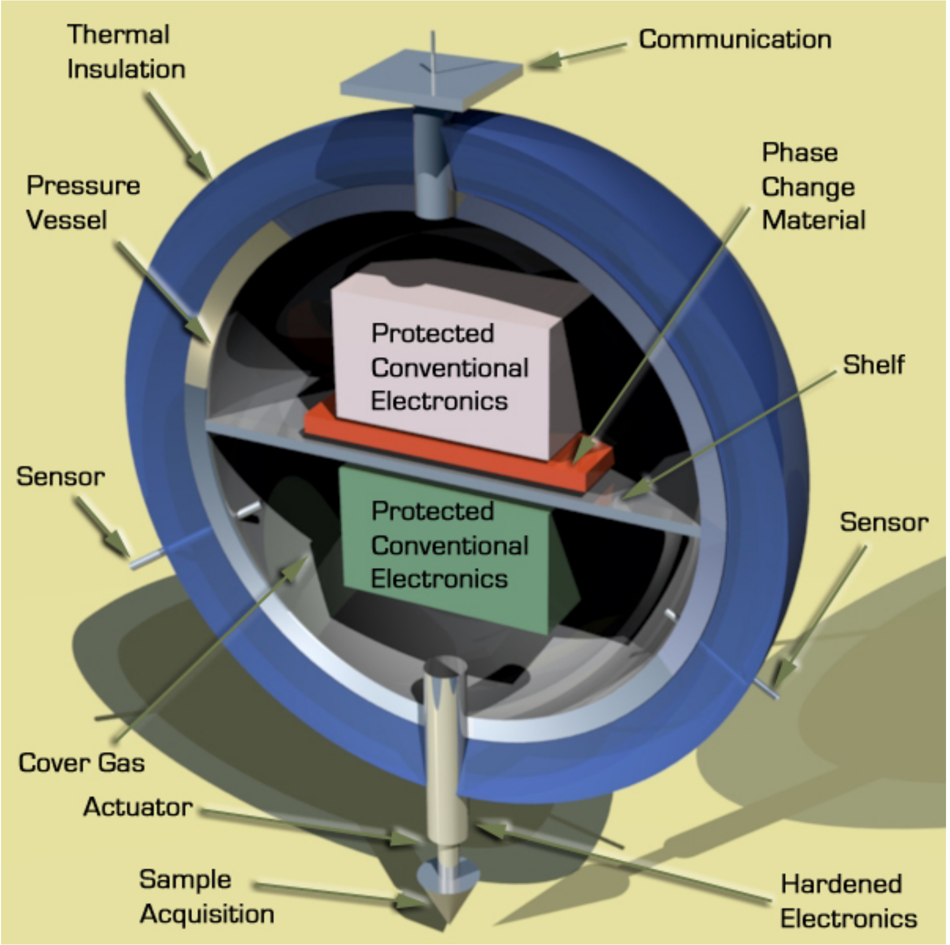


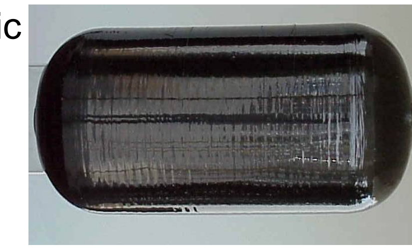
Illustration of pressure and temperature mitigation

PRESSURE MITIGATION

Pressure vessel materials:

- Monolithic metal shells
  - Steel, aluminum: low specific strength, not suitable for Venus application
  - **Titanium**: sufficient specific strength for Venus application
- Carbon fiber reinforced composite over-wrapped pressure vessel
  - Well developed and offer significant mass reduction compared to metallic shells
  - BUT unable to survive Venus temperatures (matrix resin component)

Monolithic pressure vessel



Carbon fiber reinforced shell

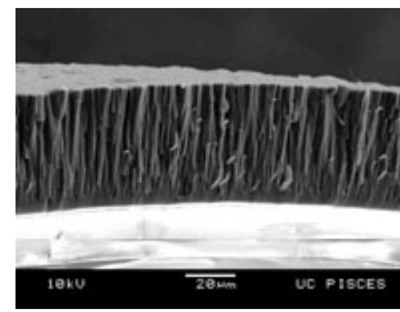
New technologies:

1) **Beryllium shell** using powder metallurgy (PM) and Hot Isostatic Process (HIP)

   to create a light weight monolithic shell with a high heat capacity,

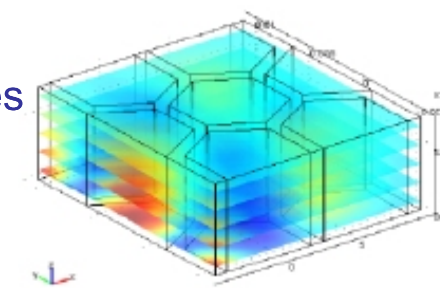
2) **Silicon Carbide/Titanium Matrix composite shell**, which also uses HIP and

3) **Honeycomb sandwich shell** structure using Inconel or possibly titanium.



Beryllium shell cross section

The development of manufacturing methods to produce spherical shapes is one of the biggest challenges of this technology.

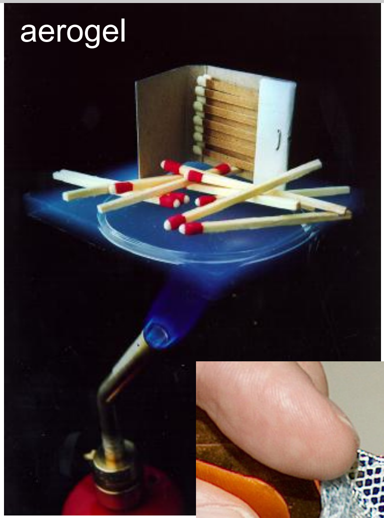


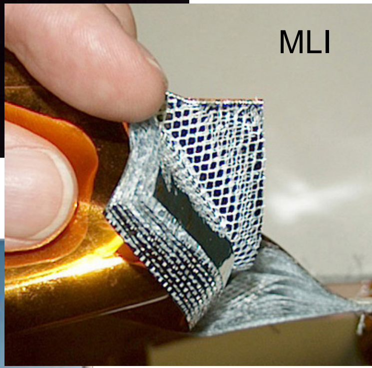
Honeycomb structure

> The mass of a titanium pressure vessel can be reduced by 50-65% by using new material and manufacturing methods

TEMPERATURE MITIGATION

- **Passive thermal control**:
  - Aerogel:
    - very low thermal conductivity, ~0.1 W/mK; density ~20 kg/m^3 (good insulation, no conduction)
  - Metal foams and ceramic foams:
    - for high-T, high heat flux applications
  - Multi-layer insulation (MLI):
    - made of closely spaced, and layered Mylar or Kapton, coated with thin film of aluminum, silver or gold (great performance in vacuum)
  - Phase change materials (PCM):
    - High transformation temperature; high latent heat; low density;
    - Paraffin; Paraffin like polymeric material that dissipates ~250 kJ/kg (solid-to-liquid transition)
  - Cover gas:
    - Xenon, Krypton, Argon: low thermal conductivity





- **Active thermal control**:
  - Active cooler for long lived missions
    - Potentially powered by specially developed Stirling Radioisotope Generator

Single-stage pulse tube cryocooler

HIGH TEMPERATURE ELECTRONICS

Technological Limits for Components

Extreme high temperature/high pressure environments are unique to space missions

Temperature (°C)

500

Hard solders melt at ~ 400°C → 400

TFE Teflon degenerates at 370°C

Silicon electronics can't operate above 350°C →

Limit of commercial and military applications is currently about 350°C

Magnets and actuators operational limit is ~ 300-350°C

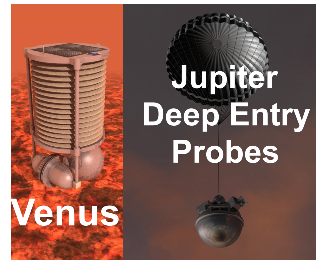
300

200

Soft solders melt at ~180°C
Connector problems start at ~150°C →

Water boils @ 1 atm at 100°C → 100

25

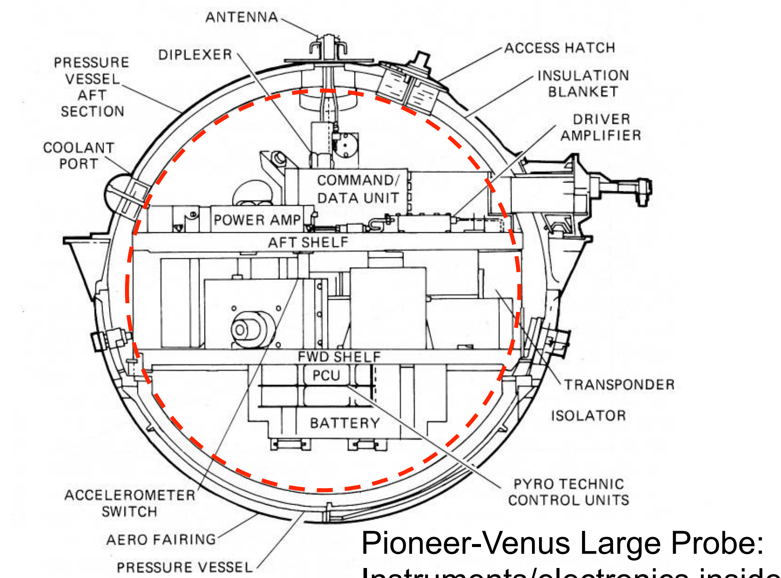


Monitoring of fossil processing

Military

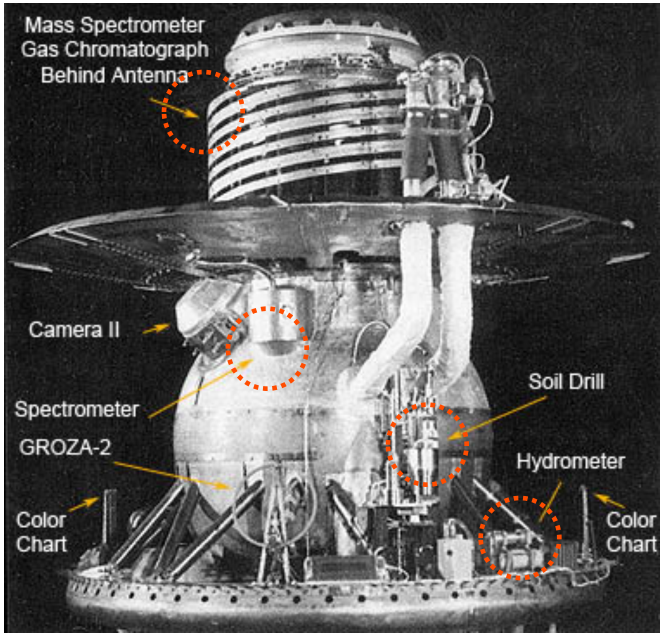
Terrestrial Applications

- **Electronics inside the pressure vessel**:
  - Can be **thermal-controlled**
  - Using a combination of **insulation** and passive or active **cooling**
  - Most suited for subsystem that **does not generate significant amount of heat**, requiring high power to maintain the internal environment



Pioneer-Venus Large Probe: Instruments/electronics inside

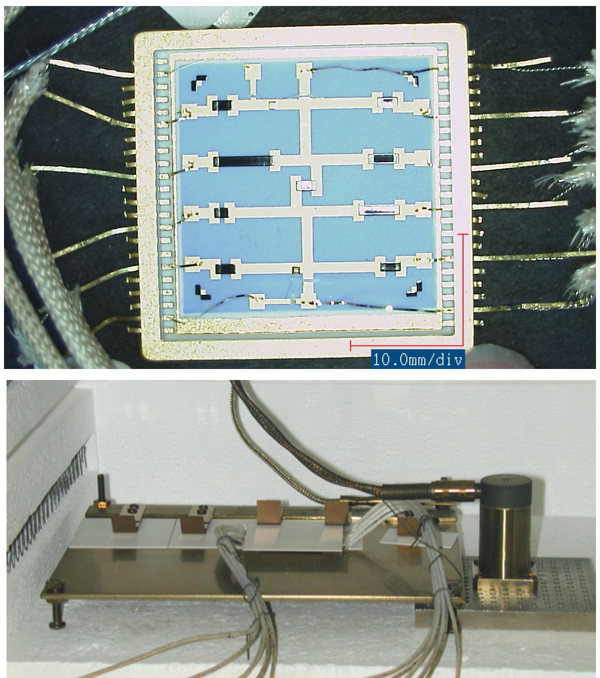
- **Electronics outside the pressure vessel**:
  - Development of **500°C tolerant electronics**
  - Allow for placing **high heat dissipating subsystems outside**
  - This would **improve cooling system efficiency**
  - Would reduce pressure vessel size
  - Increase reliability and lifetime of mission



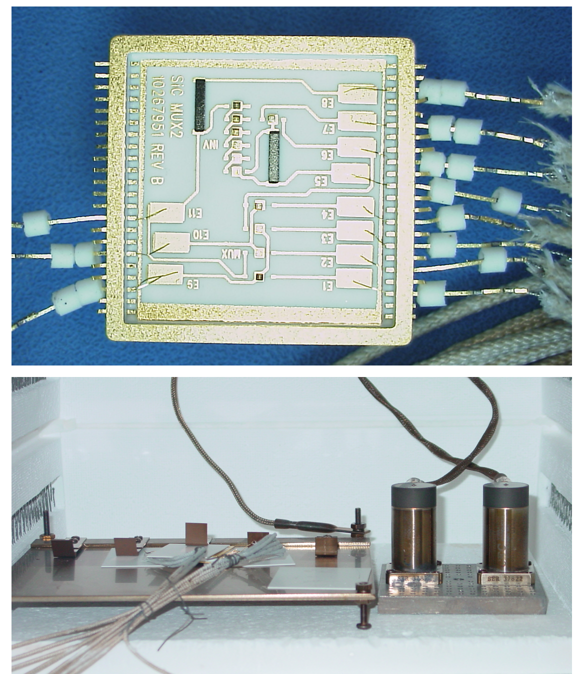
Venera 13: some instruments placed outside p/v.

HIGH TEMPERATURE ELECTRONICS

- **Outside** the thermally controlled pressure vessels **high-T tolerant electronic** could be used. For example,
  - **Silicon** devices **up to 200°C**,
  - **Silicon-on-insulator up to 300°C**, and
  - **Solid-state thermionic vacuum** devices **up to 500°C**.



Photographs of a high-T amplifier circuit (a) and test configuration (b)



Photographs of a high-T multiplexer circuit (a) and test configuration (b)

- **Power Storage**:
  - **Short in-situ** missions to Venus, and probes to Jupiter could be supported with **batteries**.
  - **High-T batteries** could be placed **outside of the pressure vessel**, which could save mass, if the energy density is improved for these batteries.
  - **Primary High-T batteries**:
    - Lithium and Sodium batteries → could operate in the 325 to 480°C range
    - Lithium-sulphur batteries → could operate in the 350 to 400°C range
    - Practical energy densities ~100-150 Wh/kg
  - **Secondary High-T batteries**:
    - Based on molten salts, alkali halides, and/or solid electrolytes
    - Most promising: Sodium-Nickel Chloride battery with molten salt
      - Functional at ~460°C; with energy density up to ~130 Wh/kg

- **Power Generation for long-lived Venus in-situ missions**:
  - Would require a **special Stirling Radioisotope Generator** (SRG), which would also
  - provide **active cooling** to the spacecraft during in-situ operations.
  - The SRG should **tolerate high pressure**, **temperature**, and the **corrosive atmosphere**.
  - Aerial mobility mission would introduce **mass and volume limit**

- RPS baselined mission architectures must **address all mission phases**
  - Earth Storage; Launch; Cruise; EDL; In-situ operations

SunPower Stirling Convertor

Cryocooler

MOBILITY TECHNOLOGIES

- Proposed Venus missions consider:
  - **aerial** mobility at **low**, **medium** and **high altitudes**, and **surface** mobility
  - representing different technology challenges.

- Finding a single **balloon material** that could **withstand** the **high temperature** and **pressure** at these altitudes is challenging. Selecting suitable **parachute materials** is also important
  - Poly-p-phenylenebenzobisoxazole (**PBO**) (high-T tolerant / limited experience)
  - **Teflon** coating (acid resistant / brittle at high-T)
  - **Zylon** (heat resistant / low corrosion tolerance)
  - Two-balloon system design

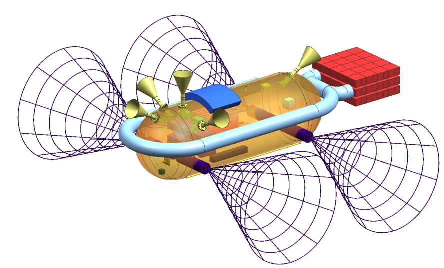
- Near the surface a cylindrical **metallic bellows**, made of thin sheets of stainless steel could be used.

- **Surface mobility** would only provide limited traversing, but good surface contact for sampling

High/mid altitude balloons

Low altitude Metallic bellows

Parachutes



Surface rovers

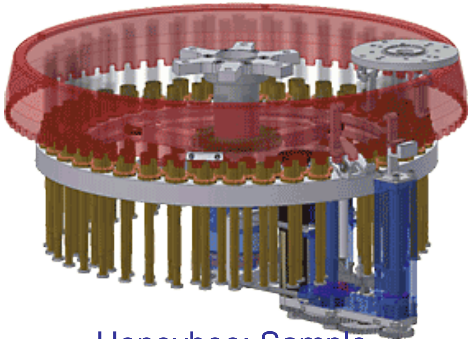
SAMPLE ACQUISITION & MECHANISMS

- Sample acquisitions and mechanisms directly interface with the extreme environments and should be tolerant to it

- Venus in-situ missions require **sample acquisition** from at least **10-20 cm below the surface**.

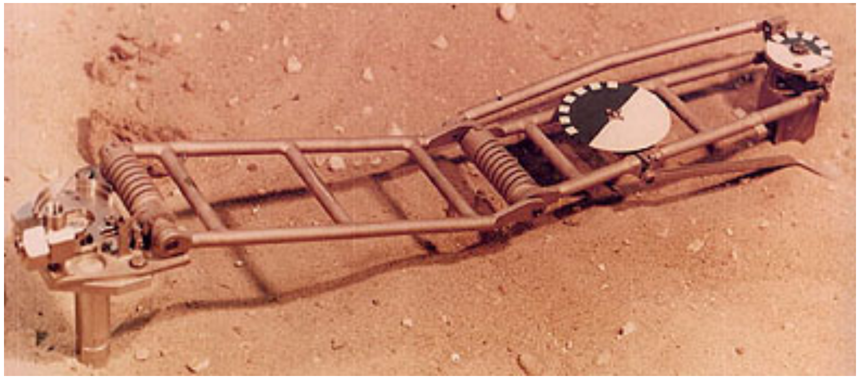
- Key components include:
  - **high-T motors & actuators,**
  - **gear boxes,**
  - **position sensors,**
  - **cabling, and mechanical devices,**
  - **sample acquisition and transfer systems**.

- Atmospheric sampling is a requirement for Jupiter deep probes as well.



Honeybee: Sample processing

Honeybee: Mini-corer

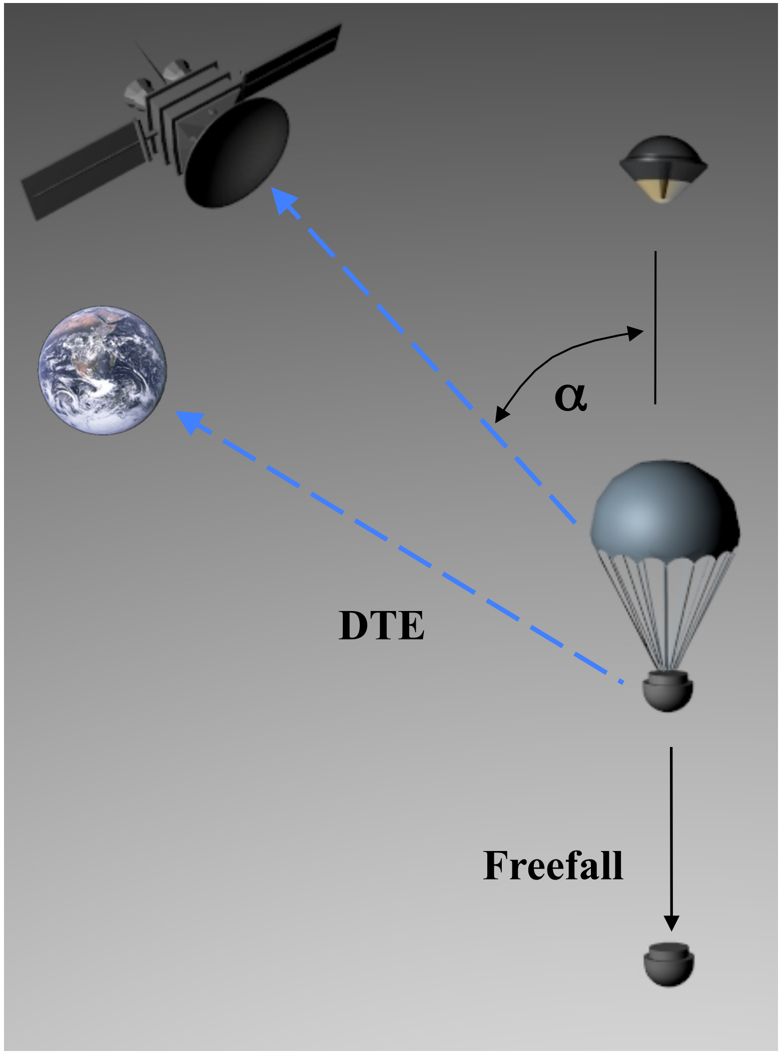


Venera 13: penetrometer

Honeybee: robotic joints

Honeybee: high-T motor

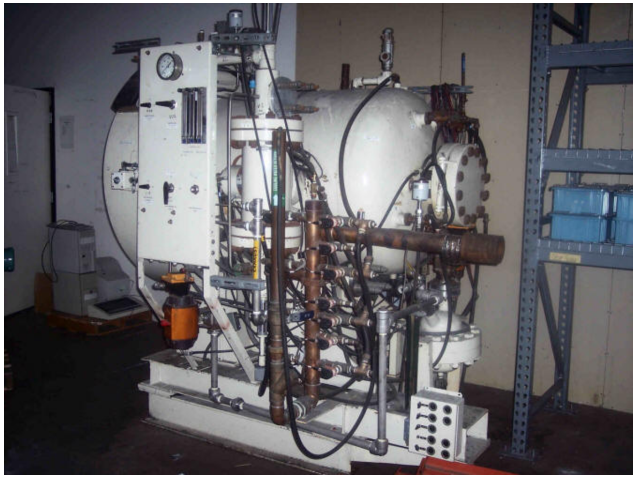
- **Telecommunication system sizing** is dependent on
  - power and antenna sizing
    - on the sending and receiving ends,
    - their separation distance,
    - the chosen frequency,
  - Environmental effect,
    - E.g., **attenuation***
  - And mission architectures
    - Relay
    - Direct-to-Earth.



Note: * For Jupiter probes, for example, the optimal communication frequency is **L-band** (~1.387GHz), since at higher frequencies **attenuation** by ammonia & water vapor impacts the link, while at lower frequencies natural **synchrotron** radiation introduces noise

- Recent work on the **properties of CO_2** at high pressures and temperatures (when it enters a **supercritical state**) indicate that it is **important to test components in relevant environments**.

- This could prevent **anomalies**, such as the one experienced by the **Pioneer-Venus probes at 12.5 km** from the surface of Venus.
  - P-V assumed that both nitrogen and carbon-dioxide are chemically inert,
  - P-V was tested in 500°C nitrogen & 100 bars, substituting for CO_2
  - NOT tested in high temperature / high pressure carbon dioxide!



Ref: Rebuilt 1987 Brew Sinterhip Vacuum Furnace (illustration example only)

VME – SUMMARY OF ENABLING TECHNOLOGIES

Telecom *(not shown)*
-Pointing DTE vs. Relay
-Power requirements

Mobility Technologies
- Metallic bellows ("balloon")
- Buoyancy control
- Lifetime / leak rate / corrosion
- Materials (bellows; parachute)
- *Surface mobility (not shown)*

RPS & Active Cooler
- Heat rejection at high T
- Active cooling to payload

Energy Storage (not shown)
- High temperature batteries inside pressure vessel

Technologies must mitigate the extreme environments
- High temperature (~460°C)
- High pressure (~92 bars)
- Corrosion (supercritical CO_2)

Long-lived in-situ exploration of Venus requires **significant technology development**, that is common to all mission architectures – VME aerial mobility / rover / static lander

Venus Mobile Explorer - VME: artist's concept

Pressure Control
- Materials (e.g., titanium, honeycomb, composite shell; beryllium shelf)
- Material creep
- Mass reduction with developments
- Volume (component miniaturization)

Thermal Management & Control
- Passive control: aerogel; PCM; MLI
- Active control: see RPS

Component Hardening
- Inside pressure vessel
- High temperature electronics
- Electronic packaging
- Science instruments
- External components / sensors
- Imagers / Optics (at interface)

Electro-Mechanical Systems
- Exposed to external environment
- Actuators, arms, moving parts
- Sample acquisition and transfer
- External valves
- Antenna gimbals

Testing for Extreme Environments
- At relevant pressure, temperature, atmospheric composition

Hypervelocity Entry *(not shown)*
- TPS; aeroshell

- Proposed **in-situ missions to Venus** and **deep entry probes to Jupiter** must be: *scientifically interesting*; *programmatically affordable*; enabled by appropriate *mission architectures*; and *technologies* to achieve mission success.

- These missions will encounter technology challenges, due to the **extremely environments**. (e.g., T ~480°C; p~92 bars; for Venus missions: highly corrosive atmosphere).

- **Systems architectures** can help to decide which components could be exposed to the environment, and which technologies will require consistent protection.

- Key **technologies** for in-situ Venus and Jupiter missions include:
  - **Technologies for high temperatures**, including passive or active thermal cooling;
  - **Pressure vessels**;
  - **High-temperature electronics**;
  - **Energy storage & generation**; and
  - **High-temperature mechanisms**

- **Current technologies limit** deep probes and landers **to a few hours of operation**;

CONCLUSIONS (2 of 2)

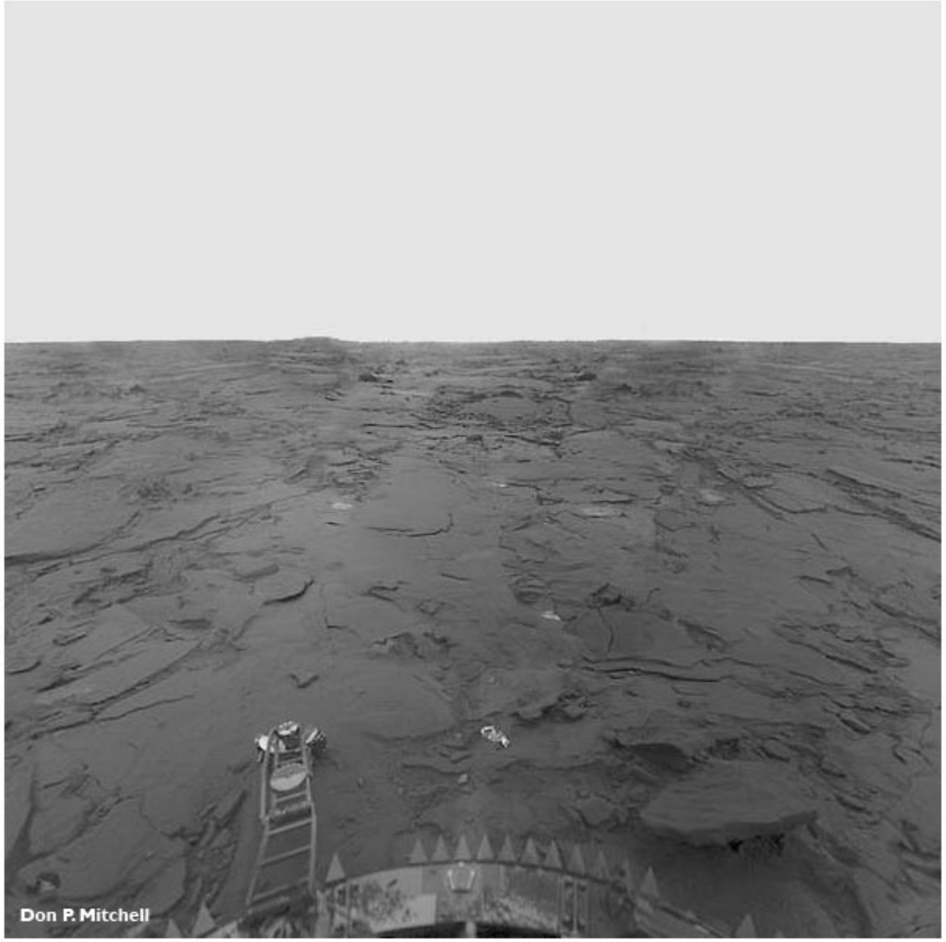
- **Long-lived Venus missions** near the surface must go beyond today's passive cooling, and would **require active cooling** to "refrigerate" the thermally controlled avionics and instruments. (Active cooling would be **coupled with** a specially designed **Stirling Radioisotope Generator**.)

- Current states of practice technologies do not support **long lived In-situ Venus missions**, and heritage technologies might not be available for the **proposed JDEP mission**. Enabling these missions could **require substantial technology investment**.

- **Planetary extreme environments** and related technologies **are unique to space agency driven missions**, thus, **agencies** are expected to **take the lead in the development of these critical technologies**, with support from industry and academia.

- Thus, findings from **EE Technology Assessments** could **help NASA** with
  - Identifying future **technology investment** areas;
  - **Enable or enhance** planned SSE **missions**;
  - **Reduce** mission **cost** and **risk**.

The end



(Venera data post-processed by Don P. Mitchell)

Note: detailed information on this topic can be found in the following reports:

- “Extreme Environments Technologies for Future Space Science Missions”, Lead Author: Elizabeth Kolawa, Jet Propulsion Laboratory, Report number: JPL D-32832, June 2007
- “Solar System Exploration - The Solar System Roadmap for NASA’s Science Mission Directorate”, Technical Report JPL D-35618, National Aeronautics and Space Administration, Washington, D.C., USA, Sep 2006